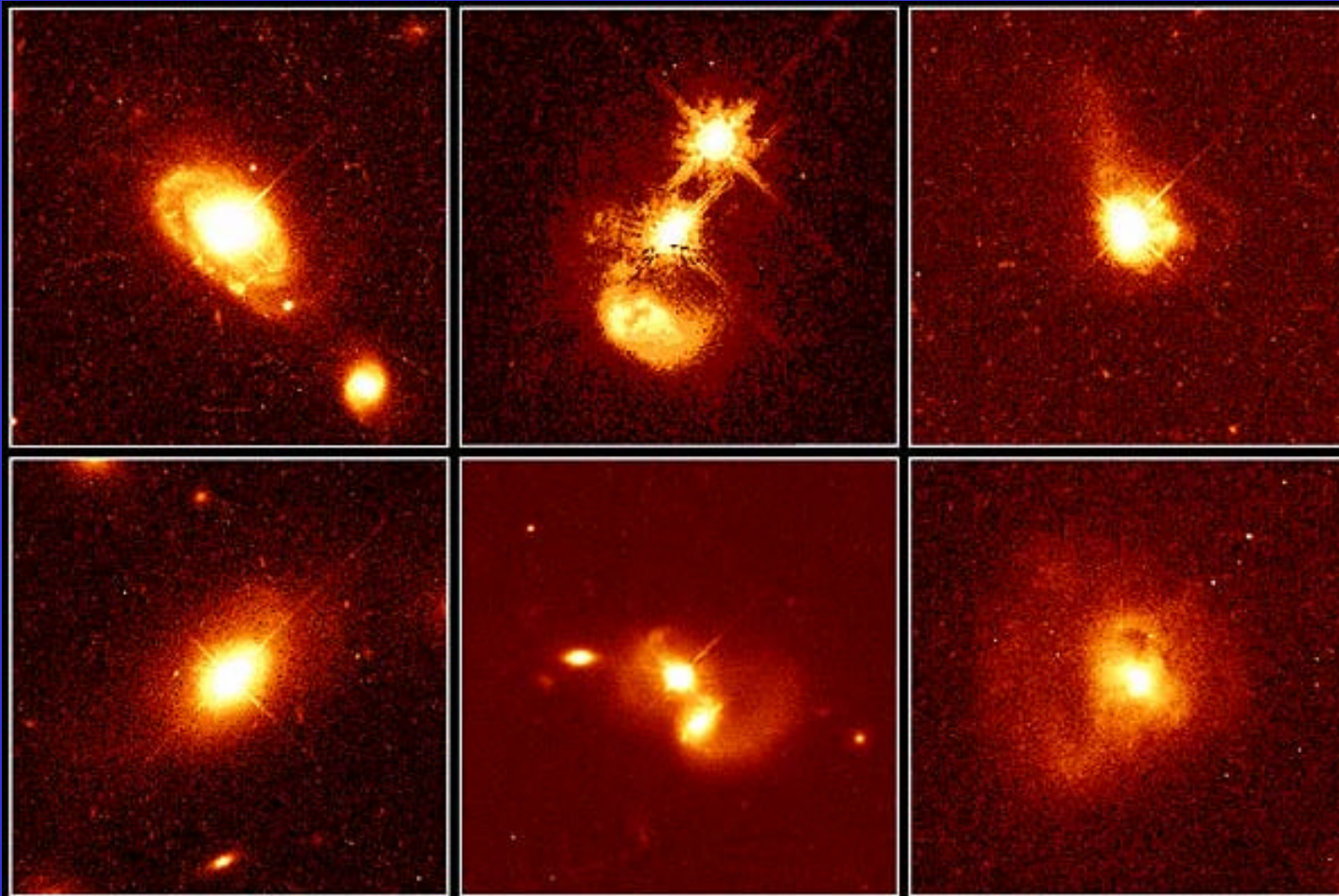# Active Galactic Nuclei: Powered by Supermassive Black Holes (10^8 M$_{sun}$)
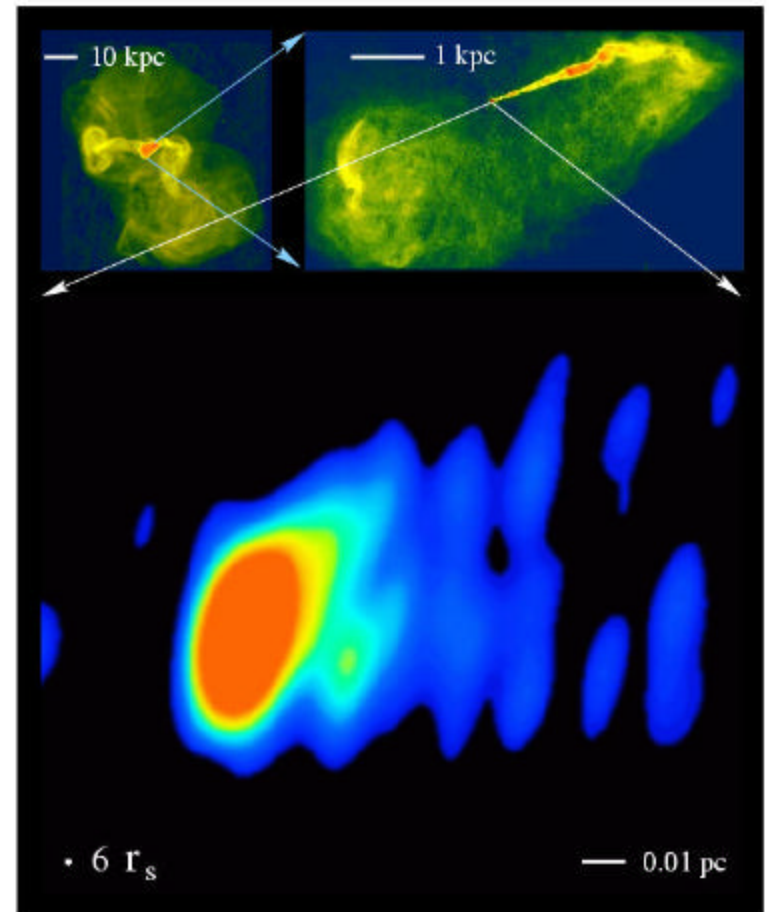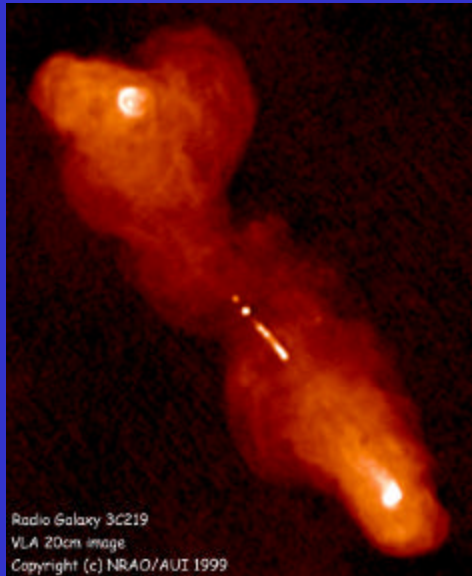

In optical

Quasar Host Galaxies   HST • WFPC2

PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

In Radio …

Radio Galaxy 3C219
VLA 20cm image
Copyright (c) NRAO/AUI 1999

Radio Galaxy 3C28B
VLA 4cm image
Copyright (c) NRAO/AUI 1999

10 kpc

1 kpc

· 6 r$_s$

0.01 pc

Questions

❑ **Are there wide-spread magnetic fields in the inter-galactic medium (IGM)?**

     ➢ **Active Galactic Nuclei:**

       Radio Galaxies, Radio loud QSOs, …

❑ **Dynamically important? Total energy content?**

❑ **Impact on the physics of IGM?**

❑ **How to observe them?**

The Magnetized Universe Project

•Energy Production:
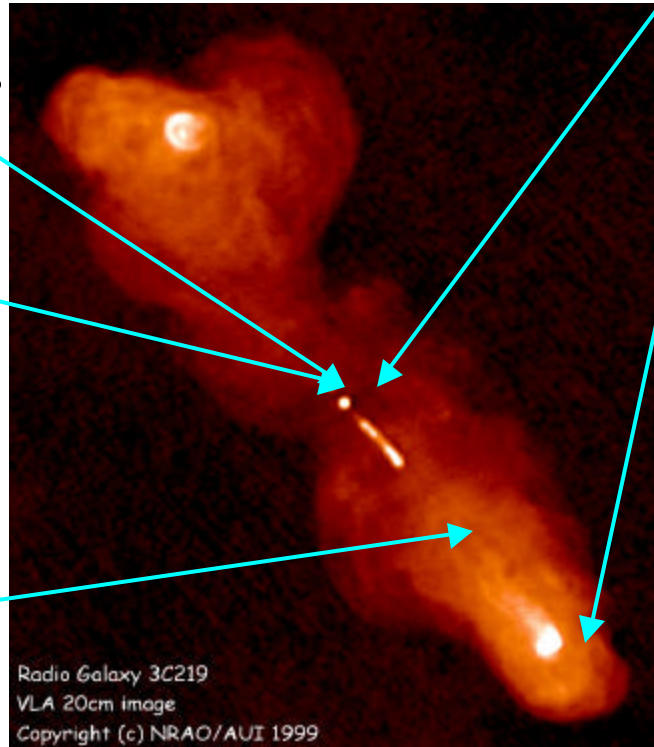
❖how to form SMBH?

❖Accretion disk physics

•Energy Conversion:

❖Gravitational →

    Magnetic (dynamo)

•Energy Dissipation:

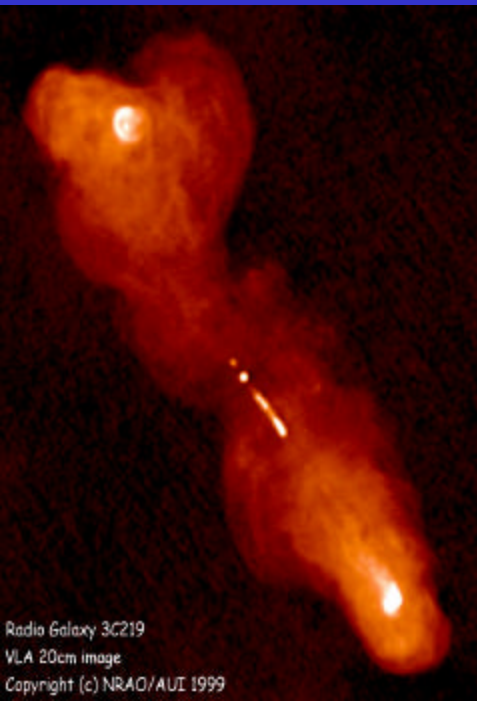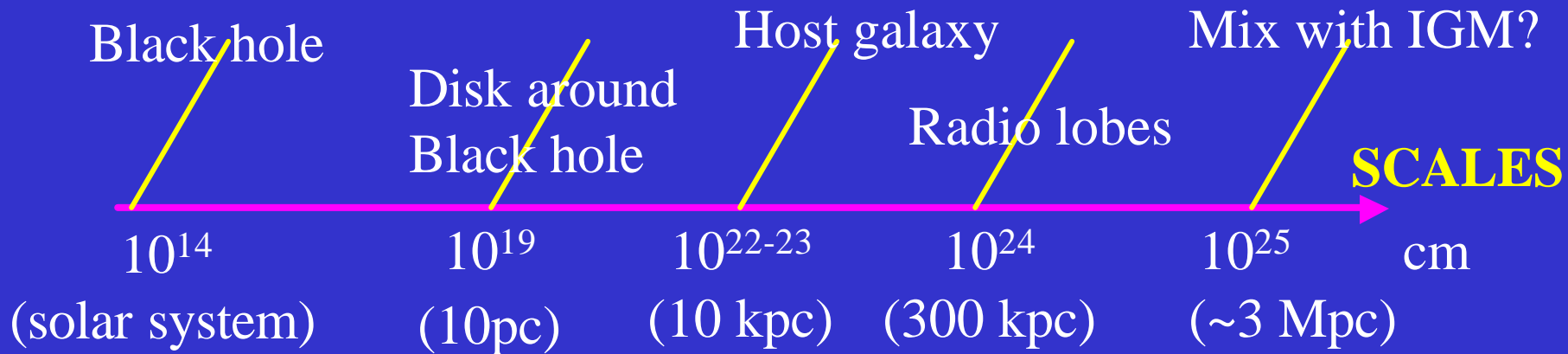❖how to dissipate magnetic energy?

❖How to accelerate particles?

•Energy Transport:

❖how to collimate jets/helix?

❖how to form radio lobes?

•Astro implications:

❖how do lobes expand?

❖impact on cosmic structure formation

❖how to detect the wide-spread B fields?

Radio Galaxy 3C219
VLA 20cm image
Copyright (c) NRAO/AUI 1999

Parameters

Black hole

Disk around
Black hole

Host galaxy

Radio lobes

Mix with IGM?

SCALES

10^{14} 10^{19} 10^{22-23} 10^{24} 10^{25} cm

(solar system)   (10pc)   (10 kpc)   (300 kpc)   (~3 Mpc)

Radio Galaxy 3C219
VLA 20cm image
Copyright (c) NRAO/AUI 1999

- **Electron energy: tens of GeV**
- **Magnetic fields: 0.5 – 5 mGauss**
- **Density: ~10^{-6} cm^{-3} (thermal)**
- **Total current: I ~ B R ~ 10^{18} – 10^{19} A**
- **drift velocity: ~10 mm/sec (!) to relativistic ~ c**

Magnetic Lobe Formation

➢ **Magneto-static limit: (e.g., Lyden-Bell'96)**

➢ **Assumptions, Steps: (Li et al.'01)**

   a) **Arcade on disk, $\mathbf{y}(r,z)$;**

   b) **Specify twist profile, $\mathbf{F}(\mathbf{y})$;**

   c) **Bounded by pressure at large distances, $p(\mathbf{y})$;**

   d) **Find sequences of equilibrium, with increasing toroidal flux, energy, and helicity;**

$\Psi = 0$ (at the bound

PP Region

$\Psi \ll \Psi_c$

$\Psi = \Psi_c$

FF

Accretion Disk

Black Hole
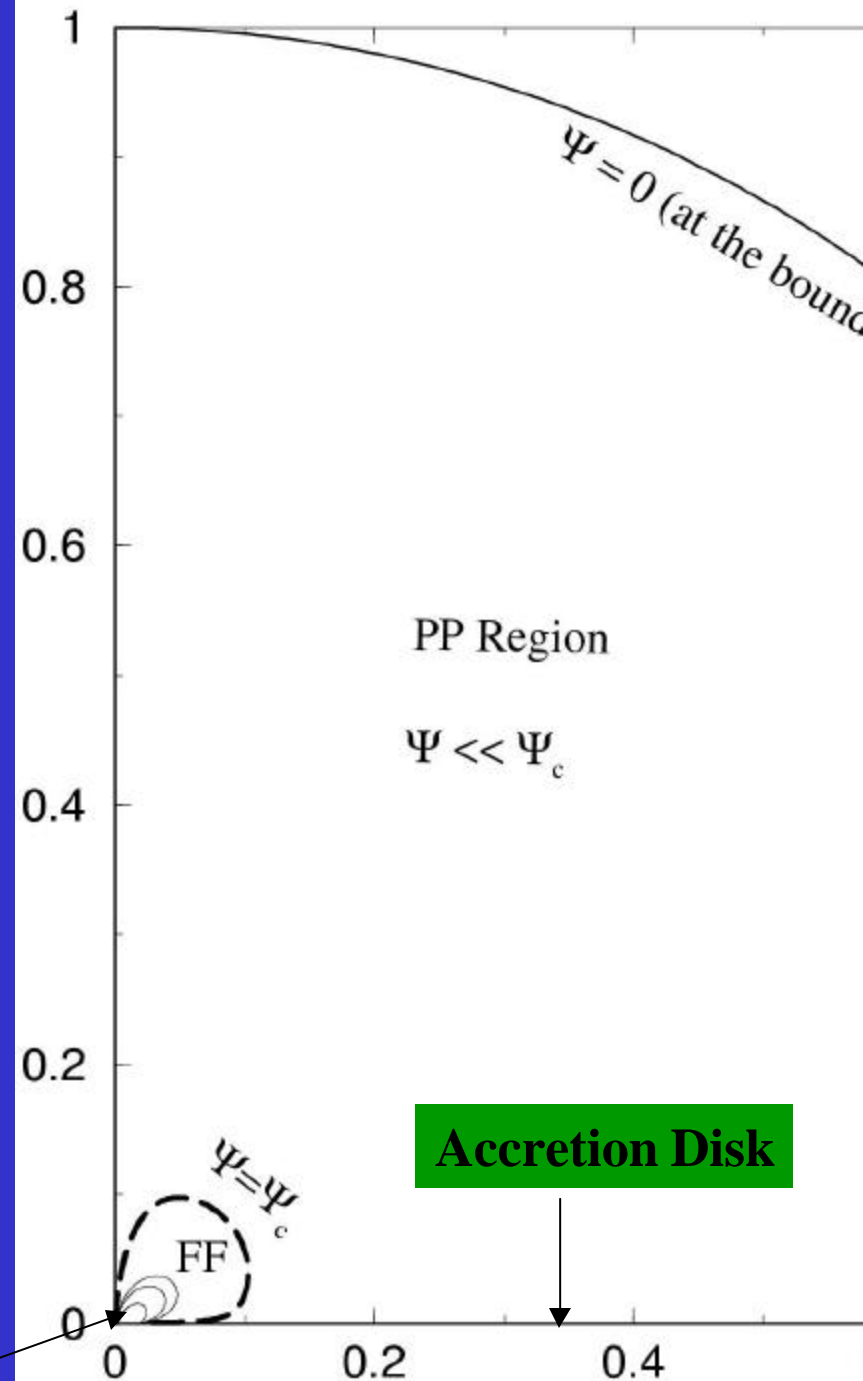
An Analytic Global G-S Solution

$$\mathbf{J} \times \mathbf{B} = \nabla p$$

$$\Delta^* \psi + d(H^2/2)/d\psi + 4\pi r^2 \, dP/d\psi = 0$$

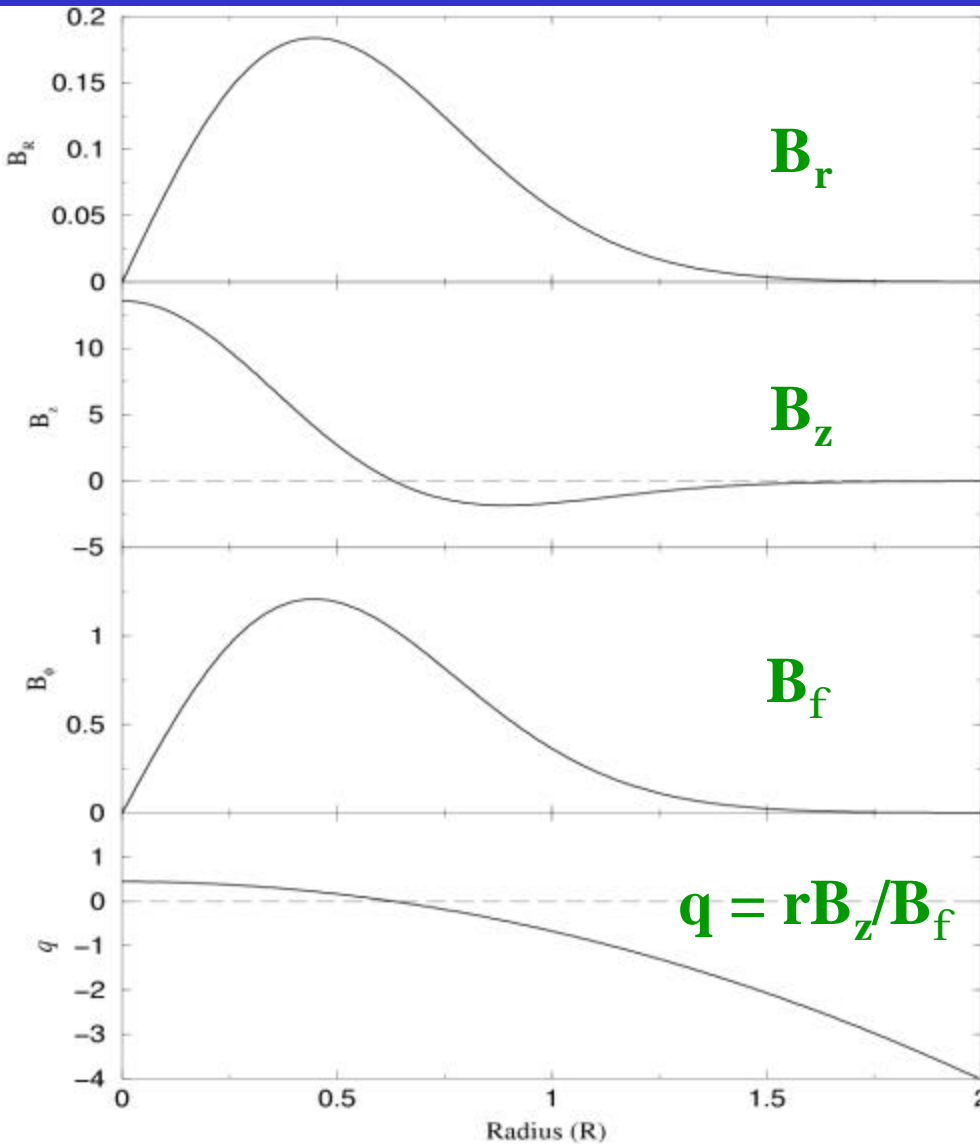$$p(\psi) = p_c \left[1 - \left(\frac{\psi}{\psi_{max}} \right)^2 \right], \quad H(\mathbf{y}) = \mathbf{l} \, \mathbf{y}$$

$$\mathbf{B} = C_0 \begin{cases} B_r = \left(2 - 2Ar^2 \right) \exp(-Ar^2) \exp(-\mathbf{m} z) \\ B_f = \qquad \mathbf{m} r \quad \exp(-Ar^2) \exp(-\mathbf{m} z) \\ B_z = \qquad \mathbf{l} \, r \quad \exp(-Ar^2) \exp(-\mathbf{m} z) \end{cases}$$

$$\text{with} \quad 8A = \mathbf{l}^2 + \mathbf{m}^2, \; C_0 = A\psi_{max}$$

$\dfrac{1}{\mathbf{l}}$ **is disk length scale,** $\dfrac{1}{\mathbf{m}}$ **is vertical scale height.**

"RFP in the sky?"

B_r

B_z

B_f

$q = rB_z/B_f$

Radius
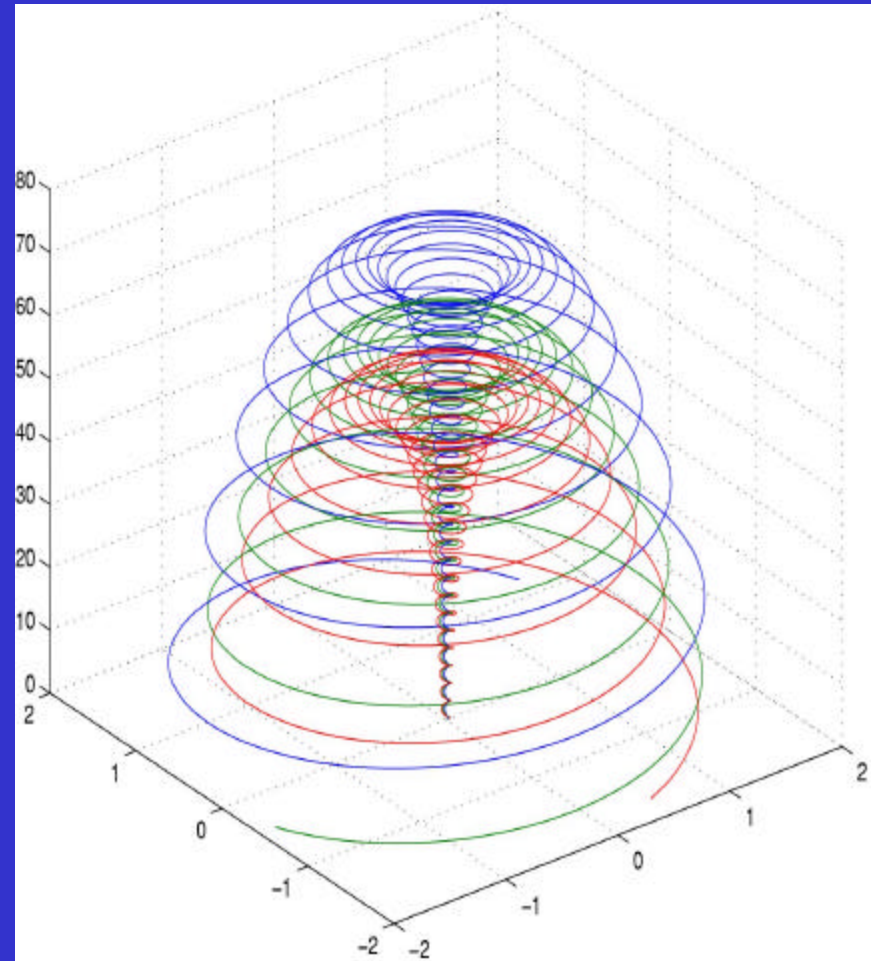
Energy : $W_B \propto l^2 y^2_{max} / m$

Helicity : $H \propto l \, y^2_{max} / m$

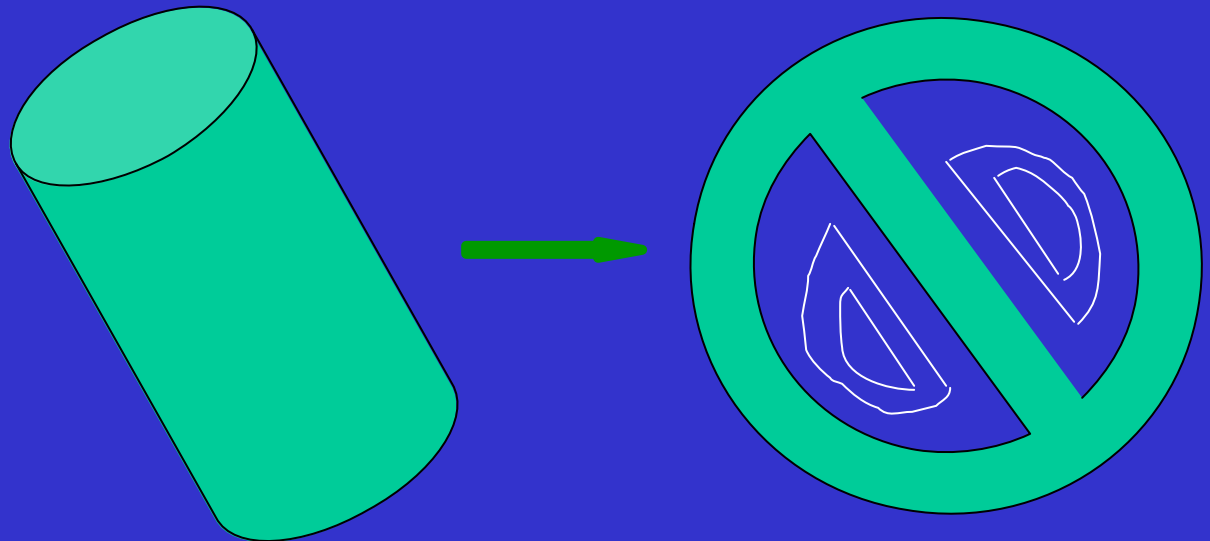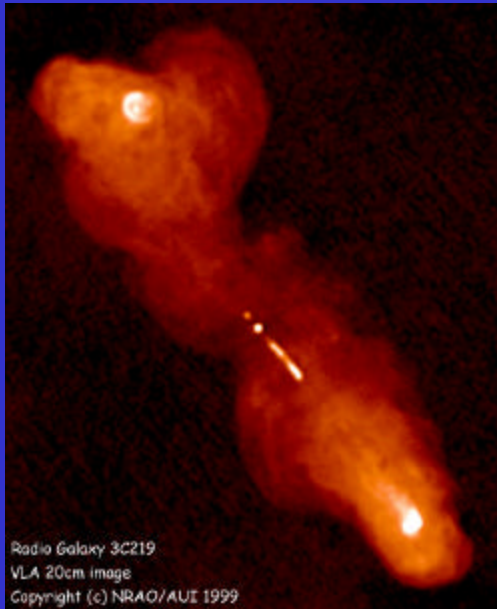**Flux ratio :** $\Phi_f / \Phi_z \propto l / m \, (\gg 1)$

Magnetic Lobe Relaxation

➢ **Actually, it is dynamic! The Alfven time for a 300 kpc lobe is 5×10^7 yrs, comparable to the life-time of the black hole.**

➢ **Short time (10^7-10^8 yrs), in a finite volume, with a finite amount of energy and helicity. Since it is over-pressured compared to its surrounding, it should evolve.**

Reconfiguration and relaxation?

Relaxation and Expansion

(Fitzpatrick & Li '03, Aspen)

Radio Galaxy 3C219
VLA 20cm image
Copyright (c) NRAO/AUI 1999

Jet/RFP:
(1) L, $a_{jet} \rightarrow Vol_{jet}$
(2) $B_z \sim J_0$, $B_f \sim J_1(r)$
(3) E_{jet}, H_{jet}

Spheromak:
(1) $a_{sp} \rightarrow Vol_{sp}$
(2) B_r, B_q, $B_f \sim j_1(r)$
(3) E_{sp}, H_{sp}

From Cylinder to Sphere….
Is energetically favorable?

(1) Volume Ratio: $V_{sp} = h\ V_{jet}$;
(2) f-flux Ratio: $F_{sp} = f\ F_{jet}$;
(3) Helicity Ratio: $H_{sp} = g\ H_{jet}$;

We get:

$$\frac{a_{sp}}{a_{jet}} \approx 1.04 \left(\frac{\eta\ g}{f^2} \right)^{1/3} ;$$

$$\frac{L_{jet}}{a_{jet}} \approx 1.53 \left(\frac{g}{f^2} \right) ;$$

$$\frac{E_{sp}}{E_{jet}} \approx 1.12 \left(\frac{f^2\ g^2}{\eta} \right)^{1/3} ;$$
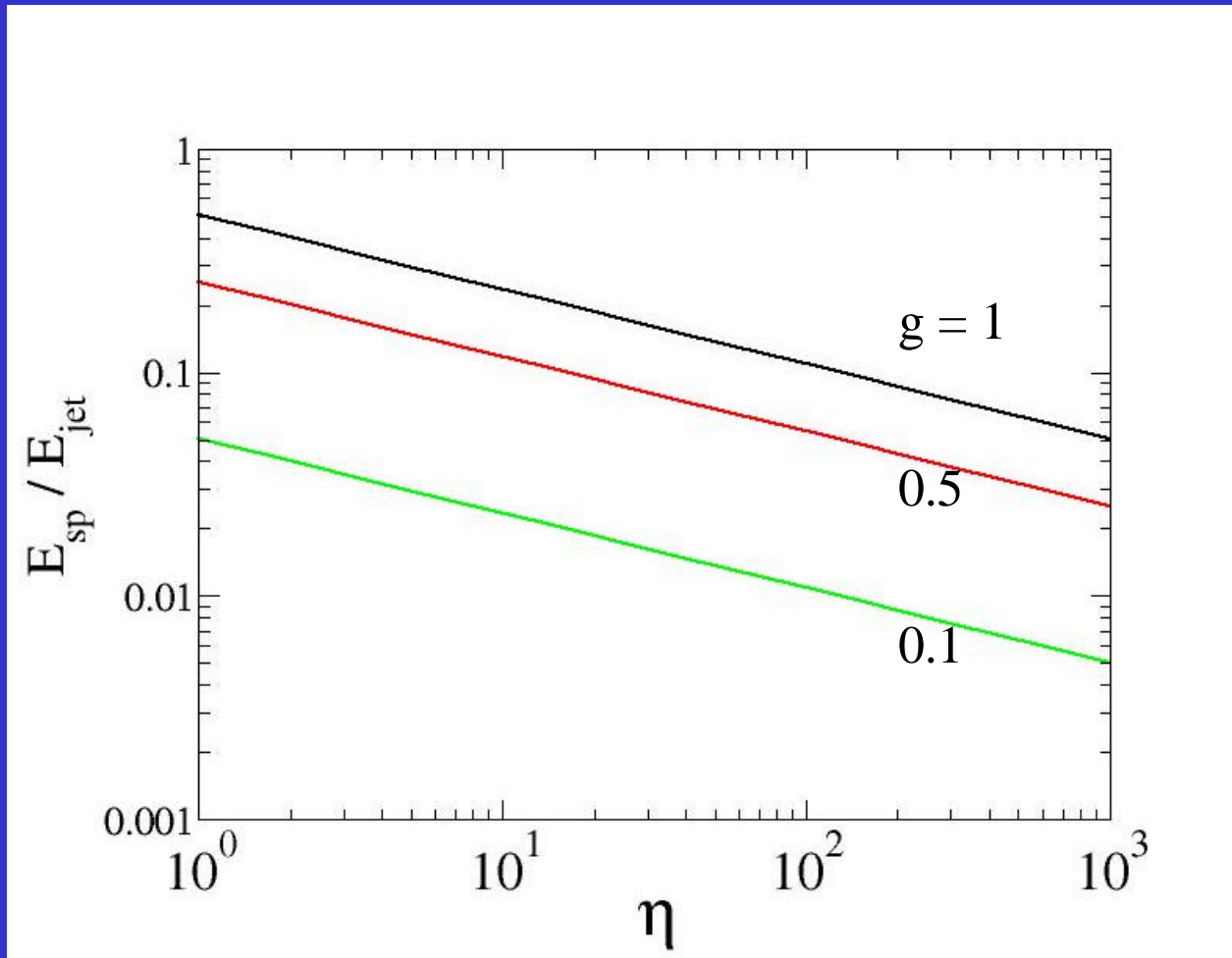
Note:
$h > 1$ (expansion)
$f < 1$ (flux conver.)
$g = 1$ (helicity conserv.)

Note that energy of the spheromak is scaled
as $h^{-1/3}$, i.e., decreasing inversely as size.

An Example

Take initial L$_{jet}$ = 500 kpc, a$_{jet}$ = 30 kpc, E$_{jet}$ = 10^{60} ergs (helicity ratio: g = 1, 0.5, 0.1, so that f-flux ratio: f = 0.3, 0.2, 0.1)
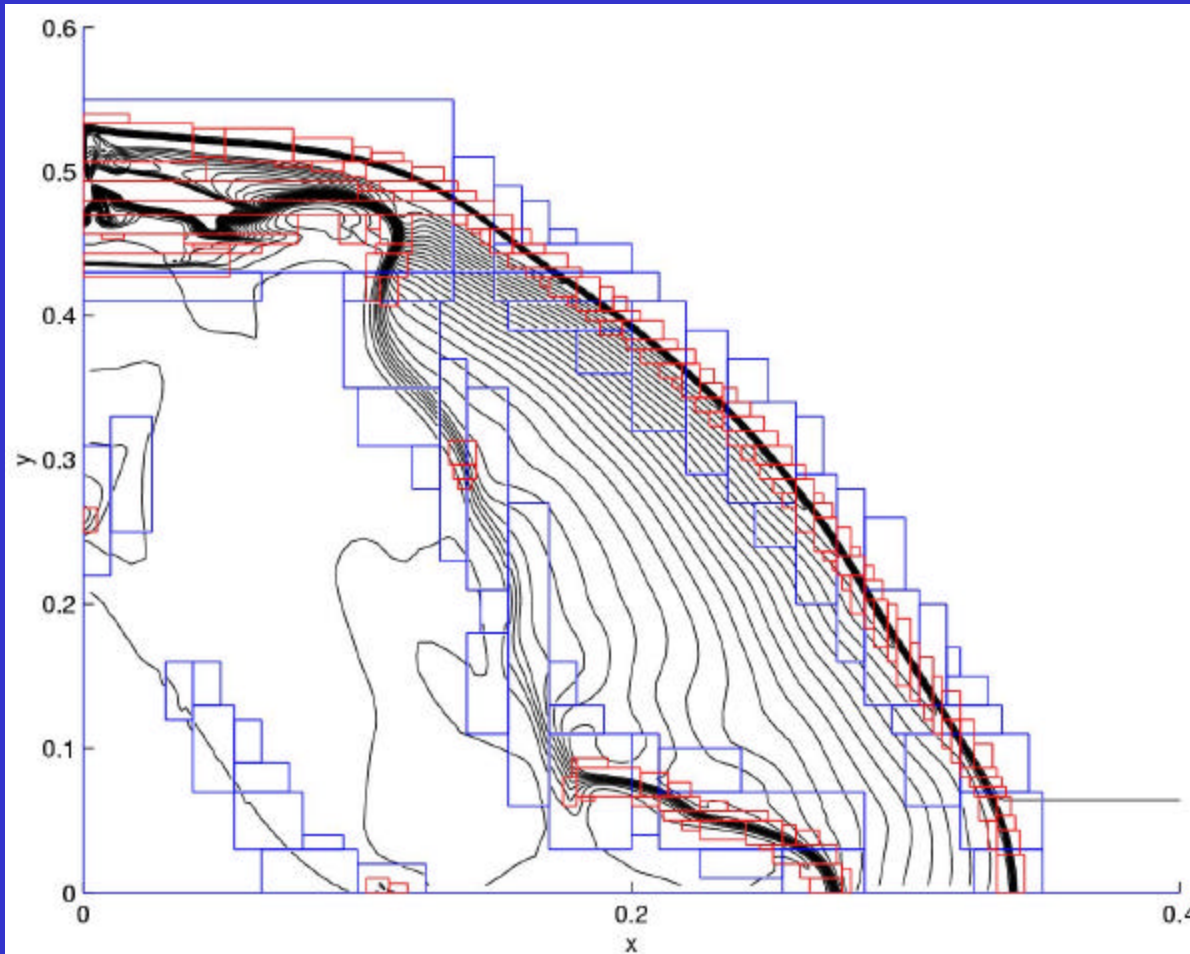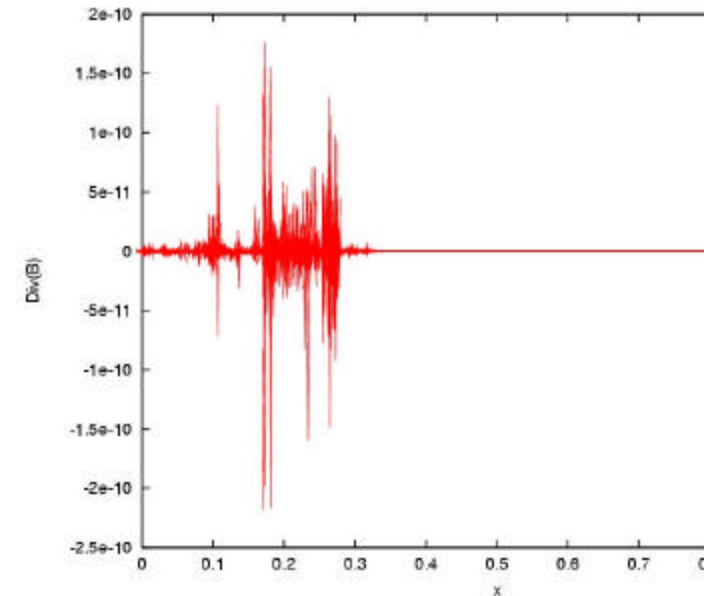

Li et al.'04

Ideal-MHD Codes

❑ Developed a new 2D and 3D ideal MHD code with AMR (Li & Li'03, ApJS), in Cartesian, Cylindrical and Spherical geometries.

❑ Developed a new algorithm of maintaining divergence free condition with AMR for arbitrary refinement ratios (Li & Li'03, JCP).

❑ Developed a new approximate Riemann solver for MHD based on HLLC (S. Li'03, JCP).
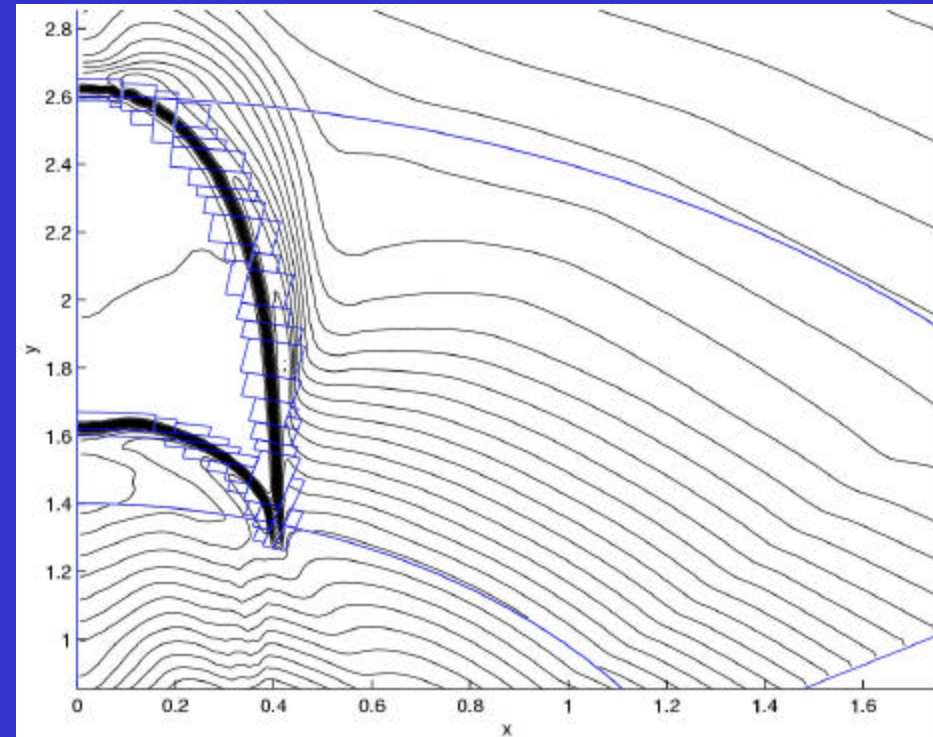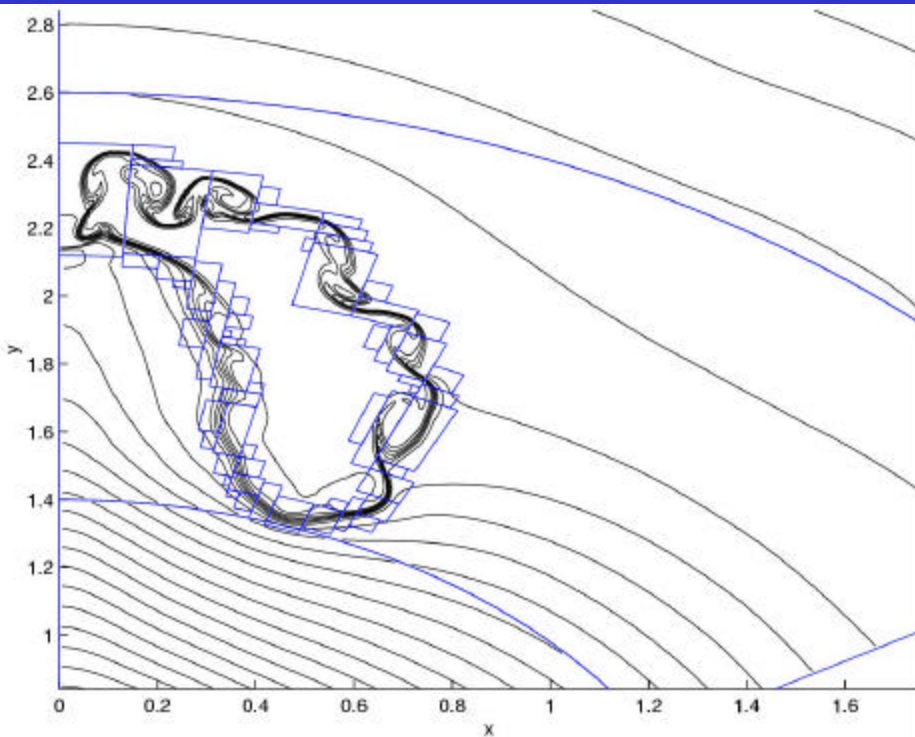
Light-Cylindrical Supersonic Jet

density

div(**B**)

Rising Buoyant Gas Bubbles in Galaxy Clusters (Li et al.'04)

without B

$B_z = const$

density

Summary

➢ **Magnetic fields from AGNs an important component in the overall energy flow of structure formation. Need to incorporate this feedback in cosmological structure formation.**

➢ **On-going cosmological MHD simulations, putting our AMR-MHD module into cosmology codes.**

➢ **Key goals: What is the volume filling factor and total dissipation of magnetic fields in IGM?**